Swash Zone Dynamics: Modeling and Data Analysis

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LONG-TERM GOALS

The goals of the work are to develop improved predictive capability for non-linear time-dependent dynamics in the swash zone. The work involves numerical computations, comparison with field and laboratory results, and theoretical analysis. The focus of the project is to quantify net onshore-offshore swash zone properties from Computational Fluid Dynamics (CFD) experiments and to compare model predictions with field and laboratory data to evaluate theoretical models of swash dynamics.

OBJECTIVES

1. Demonstrate capabilities of modeling non-linear interactions between incident and reflected waves on beaches using a Navier-Stokes model using the Volume of Fluid (VOF) method.
2. Conduct parameter studies, examining swash response (*e.g.*, bed shear stress, mean flow circulation, bore properties, run-up excursion length, *etc*.) to key physical parameters including beach foreshore slope, incident wave height, and wave frequency.
3. Develop a coupled fluid-sediment model to approximate sediment suspension and deposition and transport during swash events.
4. Interpret field data in light of model results.
5. Examine model capabilities to test properties and predictions of simplified swash zone theoretical models.

APPROACH

This work is being carried out jointly with Dr. Todd Holland and Jack Puleo at the Naval Research Laboratory, Stennis Space Center. It involves theoretical development, numerical computations, and comparison with field and laboratory results. Scientific understanding of swash zone dynamics has advanced primarily by careful field measurement of wave and beach interactions. We have introduced additional complexity to mathematical modeling of the swash zone by solving the time-dependent equations representing conservation of mass and momentum for the physical situation of water waves shoaling on a sloping beach. To this end we have adapted a two-dimensional Navier-Stokes solver for free-surface air-water flows based on the Volume of Fluid (VOF) methodology (Hirt and Nichols, 1981) appropriate for simulations of the swash zone. This model has several advantages compared to current state-of-the-art swash zone models such as Rbreak. Chief among these is the ability to represent non-linear breaking waves, depth dependency, and the ability to resolve the viscous bottom boundary layer, allowing estimates of the bed shear stress to be made. The model uses a control

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volume approach. The ability to handle a free surface is derived from allowing the control volumes to be full of water, empty (*i.e.*, air), or partially filled. Fluxes of water are calculated at each control surface interface. If the volume of fluid (VOF) is full, and its neighboring control volumes are also full, then the standard continuum approximation (the Navier-Stokes equations) are solved in fairly standard discretized form. When a control volume is empty of fluid, then, of course, constant (atmospheric) pressure is assumed. When a control volume is partially full, or when its neighbors are partially full, the methodology becomes more complex and force balances including surface stresses and inertial forces are approximated (sometimes involving projectile motion).

WORK COMPLETED

We have developed the VOF model and tested it in a series of idealized numerical experiments and against laboratory experiments we conducted at the Longshore Sediment Transport Facility (LSTF) (Figure 1.) at the Waterways Experiment Station, Army Corps of Engineers Laboratory in Vicksburg Mississippi.

Figure 1. Longshore Sediment Transport Facility showing irregular waves, the instrumentation bridge, wave gages and ADV's.

RESULTS

Numerical simulations of inner surf and swash zone motions for irregular waves were carried out using both 1D (RBREAK2) and 2D (VOF) models (Figure 2) with a Large Eddy Simulation sub-grid scale closure model. We find that the 2D model more accurately displays wave breaking and yields information regarding depth dependent fluid velocities in both the cross-shore and vertical direction. Comparisons with measurements showed that both models predicted the free surface elevation well for regular waves, however more discrepancy was observed for swash velocities and for irregular waves. The magnitude comparison yielded more evidence that the flow in the swash zone is nearly depth uniform for most of the duration of the swash cycle except in a thin boundary layer. The velocities from the VOF model had the same magnitude as those from the measured velocity data during backwash, but had a large spike below the shoreward propagating bore that exceeded the measured data. Furthermore, the VOF velocity estimates show smaller lag/lead relationships compared to the measured data.

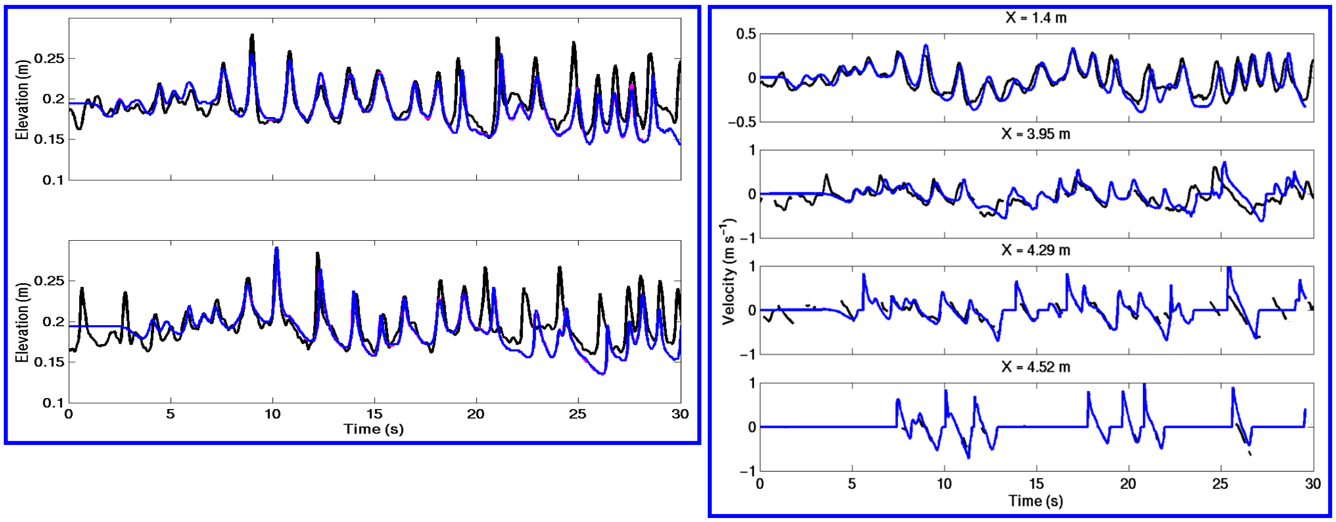

Figure 2: Sea surface comparison between lab data (black) and VOF (blue) in the swash and inner surf zone shown in the left panel indicate close agreement for the irregular wave forcing experiments at x=1.4 m (top) and x=3.0 m (bottom). The right panel compares the VOF model (blue) cross shore velocity time series to the ADV measurements (black). Negative velocities are onshore, positive velocities offshore.

Suspended sediment concentrations and fluid velocities measured in the swash zone of a high energy steep beach were also used to investigate the importance of fluid accelerations to suspended sediment transport. Swash flow acceleration was nearly constant at about one-half downslope gravitational acceleration with two important exceptions. We observed strong, short-lived periods of accelerating uprush at the beginning of the swash cycle and decelerating backwash at the end of the swash cycle (magnitudes of both approximately twice that of the expected downslope gravitational acceleration). Interestingly, spikes in suspended load (Figure 3) followed the anomalies in acceleration in a way that was not apparent from the nearly symmetric (in magnitude) ensemble averaged velocity time series. Suspended load values were largest during accelerating uprush associated with the shoreward propagating turbulent bore or swash front. During backwash, suspended loads were generally not as large. Correspondingly, suspended sediment transport rates obtained from the sediment concentration and velocity measurements showed best comparisons with a modified sediment transport model that includes a physical mechanism for enhancing transport rates due to flow acceleration. The modified sediment transport model reduced the overall root-mean-square prediction error by up to 35 % and shifted the predicted peak in uprush sediment transport rate earlier in the swash cycle, resulting in a better fit to the observations (Figure 4). These findings suggest that the inclusion of the acceleration term may account for physical mechanisms that include bore turbulence and horizontal pressure gradients typically associated with the accelerating portion of uprush.

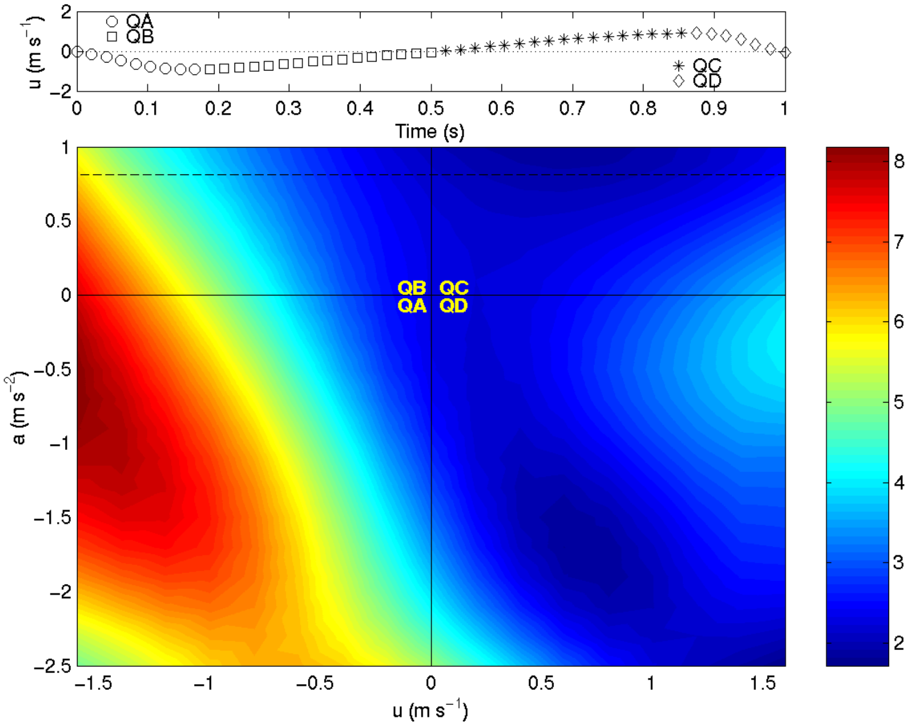

Figure 3. Interpolated suspended load (kg m^{-2}) as a function of velocity and acceleration. Dotted line is downslope gravitational acceleration and solid horizontal and vertical lines separate quadrants. Upper panel shows a velocity time history of an ensemble-averaged swash event with symbols corresponding to the 4 quadrants.

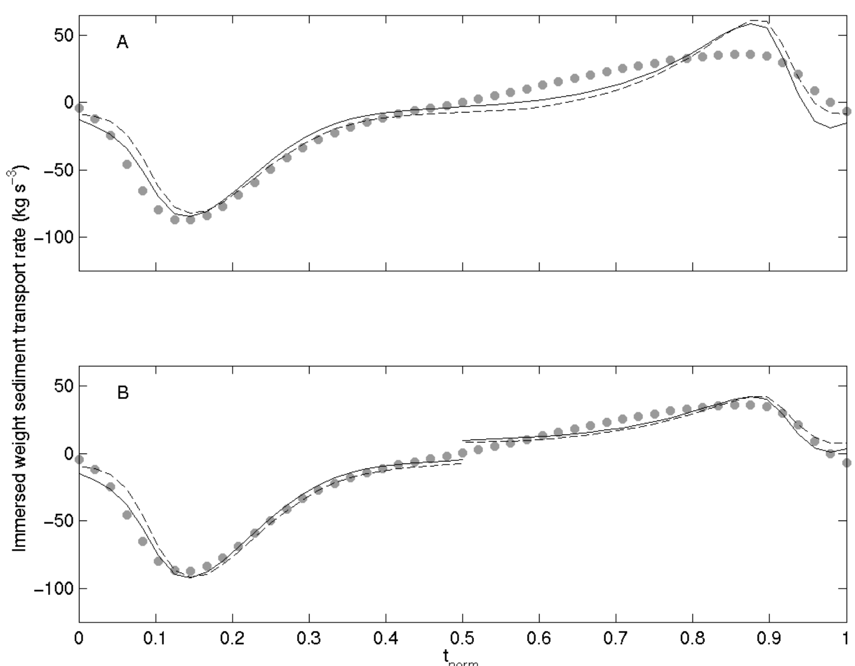

Figure 4. Suspended sediment transport rate measurements (circles) and predictions [dashed (q_B); solid (q_{pred})]. A) For the entire swash cycle. B) For uprush (negative values) and backwash (positive values) portions of the swash cycle fitted separately.

IMPACT/APPLICATIONS

Improved understanding of the swash zone has potential benefits for society in several areas. These include shore protection against beach erosion, understanding the behavior of shoaling waves and rip currents, mitigating problems associated with sediment transport, such as keeping waterways open for shipping in harbors, ports and inlets.

TRANSITIONS

The project began this year and we are testing and validating our model capabilities. Jack Puleo, NRL-SSC is working on it as part of his PhD dissertation, and has added LES to the VOF model.

RELATED PROJECTS

Dr. K. Todd Holland at the Naval Research Laboratory, Stennis Space Center, is leading the work on the laboratory and field experiments on heterogeneous beaches.

REFERENCES

Hirt, C. W., and B. D. Nichols, 1981, *Jounal of Computational Physics*, 39, 201.

PUBLICATIONS

J.A. Puleo, K. T. Holland, N. G. Plant, D. N. Slinn, 2003, Fluid acceleration effects on suspended sediment transport in the swash zone, accepted for publication in the *Journal of Geophysical Research*.

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